Nonreciprocal Acoustic Transmission using Lithium Niobate Parity-Time-Symmetric Resonators

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Abstract: Taking advantage of the piezoelectricity of lithium niobate, we achieve nonreciprocal transmission of 10 decibels for a 200-MHz surface acoustic wave using parity-time-symmetric resonators and demonstrate one-way circulation of acoustic waves.

1. Introduction

Phonons have emerged as versatile on-chip information carriers with applications ranging from microwave filters to transducers. Nonreciprocal devices are desired to control and route these high-frequency phonons. Nonreciprocal phonon transmission can be achieved by breaking the time-reversal symmetry of propagating waves. Previous demonstrations, which employ bulk media based on circulating fluids [1] and superlattices with nonlinear media [2, 3], were limited to acoustic frequencies below a few MHz. Meanwhile, ferromagnetic materials demonstrate nonreciprocal phonon device at microwave frequencies but with a weak isolation [4]. Here, we construct a nonlinear acoustic parity-time(PT)-symmetric system and enable nonreciprocal transmission. We achieve a nonreciprocity of 10 decibels for a 200-MHz surface acoustic wave (SAW) and further demonstrate one-way circulation of SAW by cascading nonreciprocal devices.

2. PT-symmetric SAW resonators

The PT-symmetric SAW system consists of two coupled SAW resonators defined by the Bragg mirrors (Fig. 1(a)). The Bragg mirrors provide more than 30 dB reflectivity over a bandwidth of 8 MHz around a frequency of 200 MHz (Fig. 1(b)). The SAW resonators exhibit three resonant modes with intrinsic quality factor up to 10^4 within the reflection band of the Bragg mirror. The interdigital transducers (IDTs) within the resonator are connected to external electronic circuits to provide the gain or loss for the SAW. Specifically, the variable gain IDT is connected (using wire bonding) to a negative resistance electric circuit implemented by an operational amplifier with feedback resistors, and the loss IDT is connected to a tunable electronic resistor. Two more IDTs are situated outside the coupled resonator system and are used as an emitter and a receiver of SAWs, for measurements of acoustic transmission.

3. Results

We numerically simulate the nonreciprocal SAW transmission in the broken PT-symmetric region (Fig. 1(c)). The PT symmetry breaking induces a stronger localization in the active resonator for the backward propagating wave than that of the forward propagating wave. The stronger localization results in a lower gain due to the saturation and leads to a lower transmission in the backward direction.

Our PT-symmetric SAW devices operate in the unbroken or broken symmetry regimes by varying the number of Bragg mirror grooves (i.e. the coupling strength) between the two resonators. An 80-groove (30-groove) mirror is used for measurements in the nonreciprocal broken (reciprocal unbroken) PT-symmetric regime. A nonreciprocity of 10.9 dB is observed in the broken PT-symmetric regime (Fig. 2(a)), while a reciprocal transmission is observed in the unbroken-PT-symmetric regime (Fig. 2(b)).

Further, we demonstrate one-way SAW circulation using two nonreciprocal devices. Expected circulating behavior is observed at the resonant frequency of the device (Fig. 3). A SAW from Port 1 is preferably transmitted to Port 2 (S_{21}). At the resonant frequency, a 20 dB higher transmission is observed in the clockwise direction S_{21} than that in the counterclockwise direction S_{31} (Fig. 3(a)). Similarly, when a SAW is excited from Port 2, a 10 dB higher transmission to Port 3 is observed than that to Port 1 (Fig. 3(b)).

4. Conclusion

We demonstrate a compact piezoelectric platform on lithium niobate for non-Hermitian and nonreciprocal acoustics. The operating frequency can be adjusted from a hundred megahertz to a few gigahertz by geometrically scaling the design [5]. Our work would enable exploration of acoustic non-Hermitian physics and extend acoustic signal processing functionalities for next-generation wireless communication.

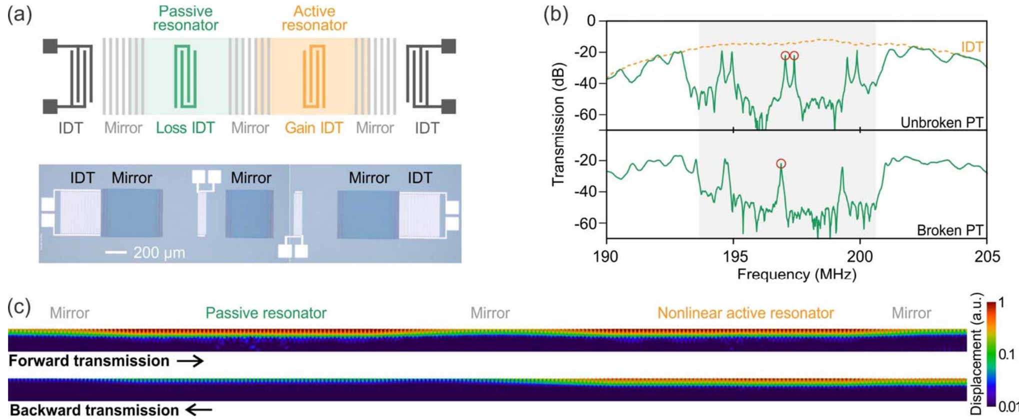

Fig. 1. Nonreciprocal phonon transmission using nonlinear PT-symmetric SAW resonators. (a) Schematic and microscopic image of our coupled SAW resonator system for nonreciprocal transmission. Loss and gain are introduced in the passive and active resonators, respectively. IDTs are used to create gain, loss and to generate and receive SAWs. (b) Measured transmission spectra of one device with a strong coupling in the unbroken PT-symmetric (reciprocal) regime and the other device with a weak coupling in the broken PT-symmetric (nonreciprocal) regime. (c) Numerical simulations of the magnitude of elastic displacement due to SAWs propagating through broken PT-symmetric (nonreciprocal) resonators in the forward and backward directions.

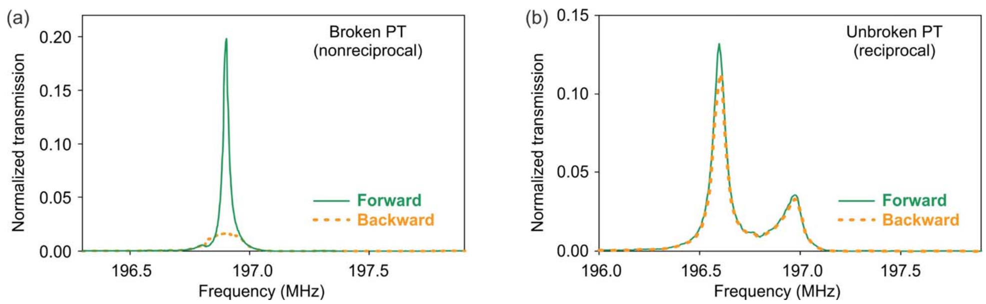

Fig. 2. (a) Nonreciprocal and (b) reciprocal transmission measurements of the SAW resonators in the broken (unbroken) PT-symmetric regime. The microwave powers applied to input IDTs are -25 dBm (3 μW) in both plots.

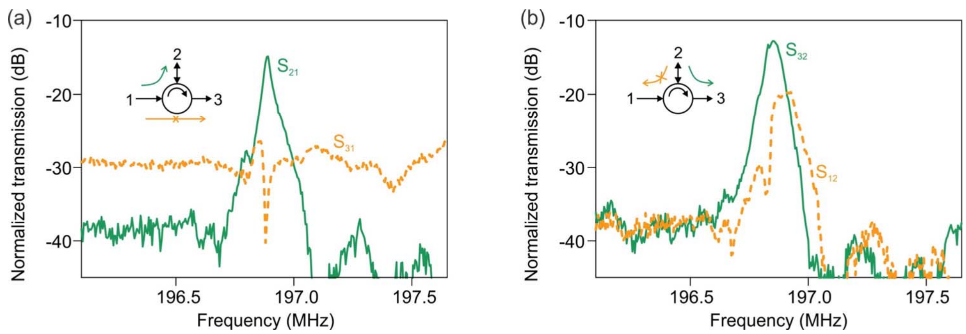

Fig. 3. One-way circulation of SAW. Transmission measurements among different ports.

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